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EXPERIMENTAL IMPLICATIONS FOR A LINEAR COLLIDER OF SUSY DARK MATTER SCENARIO

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Abstract

This talk presents the detection issues for the lightest slepton $\tilde{\tau}_1$ at a future e^+e^- TeV collider given the dark matter constraints set on the SUSY mass spectrum by the WMAP results. Two methods for measuring its mass $m_{\tilde{\tau}_1}$ and the resulting precision on the dark matter density are briefly discussed in the SUSY mSUGRA scenario with R-parity conservation when the mass difference between $m_{\tilde{\tau}_1}$ and that of the lightest neutralino is small (a few GeV). The analysis is performed with TESLA parameters in both head-on and crossing angle modes.

The talk is based on recent studies [1,2] motivated by the increasing awareness in the community of the role of an e^+e^- Linear Collider (LC) for a precise determination of the SUSY parameters which are needed to interpret the dark matter (DM) content of the universe. After the WMAP results [3] leading to an accuracy at the 10% level or $0.094 < \Omega_{\rm DM}h^2 < 0.129$ in two standard deviation range and awaiting for the Planck mission in 2007 which aims at 2%, it seems appropriate to check that a LC can do its job properly on this essential topic.

In the SUSY scenario with R-parity conservation, the lightest SUSY particle (LSP) is the lightest neutralino χ. This particle is considered as the best candidate to satisfy the cosmological constraints on DM in the universe. DM constraints have been recently re-examined [4] within the mSUGRA scenario, confronting the precise predictions obtained after the WMAP results. These data imply, for many of the benchmark points retained, a very small difference between the mass of the lightest slepton ($\tilde{\tau}_1$), the SUSY partner of the τ, and the LSP mass ($\Delta M = m_{\tilde{\tau}_1} - m_\chi$) since one of the preferred mechanism to regulate the amount of DM in the universe is the so-called 'co-annihilation mechanism'.

Previous studies have shown that the masses of both smuon and LSP can be precisely measured using the so-called end-point method [2]. Here we shall thus concentrating on the measurement of stau mass, which is relevant as the amount of DM depends critically on it.

Two methods are presented for this purpose. The first is appropriate when the stau mass is comparable to the beam energy and the expected cross section of the stau production is small. The second works when the stau mass is significantly smaller than the beam energy and the stau production cross section is large. We also address detectability issues related to different collision mode either in head-on or with a half crossing angle of 10 mrad.

The end-point method could not applied to the stau analysis as there are additional missing energies arising from neutrinos in subsequent τ decays. Furthermore, the final state particle is very soft, typically a few GeV for $\Delta M = 5\,\mathrm{GeV}$ taking benchmark point D' in [4] as a working point. Another difficulty comes from the fact that the signal cross section is often many orders of magnitude smaller than that of the Standard Model (SM) processes.

For point D' at center-of-mass energy ($\sqrt{s}$) of 500 GeV, the cross section of the signal process $e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^-$ is around 10 fb, which is to be compared with $10^5 - 10^6$ fb of the dominant SM background processes $e^+e^- \to e^+e^-\tau^+\tau^-, e^+e^-\mu^+\mu^-$ and $e^+e^-q\overline{q}$. The spectator $e^\pm$ in the background process is however predominantly peaked in the forward direction. Therefore an efficient tagging down to lowest possible angle is crucial in rejecting these background events. Quantitative studies show that the current tagging efficiency of the beam monitor calorimeter, LCAL, does not allow for a background free analysis. Such an analysis may be achieved [1] when the LCAL is fully efficient in tagging all spectator $e^\pm$ having a transverse momentum above 0.8 GeV and when additional discriminating variables are used. One such variable is the scalar sum of transverse momentum with respect to the thrust axis in the plane transverse to the beam directions. The resulting signal efficiency and background contribution from the dominant processes in the head-on collision are summarized in table 1.

Efficiency (%)	$N(\tilde{\tau}_1 \to \tau\chi)$	$N(ee \to \tau\tau ee)$	$N(ee \to q\overline{q}ee)$ with $q = c, b$
6.3 ± 0.2	316 ± 9	1.0 ± 1.0	1.0 ± 1.0

Table 1: *The efficiency, the signal and dominant background events in the head-on case for benchmark point D' at $\sqrt{s} = 500$ GeV.*

In collisions with a half cross angle of 10 mrad, there are two beam holes for the incoming and outgoing beams. The spectator $e^\pm$ may end up in the incoming beam hole resulting additional inefficiency in the veto. Studies show that these background events have an unbalanced transverse momentum of about 5 GeV due to the untagged $e^\pm$ spectator and can be efficiently eliminated with by a combined cut on the acoplanarity angle and on the angle of the missing transverse momentum vector [1]. The price to pay is however a lower signal inefficiency of about 25% with respect to the head-on mode.

To extract the $\tilde{\tau}_1$ mass with minimum luminosity, the first method consists in measuring the cross section at one energy and deduce the mass from the value of β since, at the Born level, this cross section depends on $\beta^3 = (1 - 4m^2/s)^{3/2}$, where m stands for the stau mass. Assuming the SM background is negligible and for a given integrated luminosity, the best accuracy on the stau mass measurement is achieved when the beam energy is just above the stau mass threshold [1]. For point D$'$ with $m_{\tilde{\tau}_1} = 217\,\mathrm{GeV}$, the optimum $\sqrt{s}$ is at $\sim 442\,\mathrm{GeV}$ and the resulting error on the stau mass is $\sim 0.5\,\mathrm{GeV}$ for $500\,\mathrm{fb}^{-1}$. The gain in the precision with this choice of optimum beam energy is appreciable, at $\sqrt{s} = 500\,\mathrm{GeV}$ the error would have been 1.2 GeV. The same analysis without further optimizing the selection cuts is also applied to the other relevant benchmark points. The results are summarized in table 2.

The program Micromegas [5] has been used to compute the relative uncertainty on the DM density due to the SUSY mass error measurements. This program operates without any assumption, in particular it does not rely on the mSUGRA scheme. Results listed in table 2 show, as expected, that $\Omega_{\mathrm{DM}}h^2$ depends primarily on the precision on the stau and LSP masses. The analysis, optimized for the D$'$ solution, gives satisfactory results except for point J$'$ which is almost beyond detectability.

	method one					method two			
Model	A′	C′	D′	G′	J′	SPS 1a inspired			D'
$m_{\tilde{\tau}_1}$ (GeV)	249	167	217	157	312	133			217
ΔM (GeV)	7	9	5	9	3	8	5	3	5
$\mathcal{L}$ (fb^{-1})	500					200			300
$\sqrt{s}$ (GeV)	505	337	442	316	700	400			600
σ (fb)	0.216	0.226	0.279	0.139	1.35	140			50
ϵ (%)	10.4	14.3	5.7	14.4	< 1.0	18.5			7.6
$\delta m_{\tilde{\tau}_1}$ (GeV)	0.487	0.165	0.541	0.132	> 1.0	0.14	0.22	0.28	0.15
$\delta(\Omega_{\rm DM}h^2)$ (%)	3.4	1.8	6.9	1.6	> 14	1.7	4.1	6.7	1.9

Table 2: *Different benchmark points studied in two methods are shown together with the $\tilde{\tau}_1$ mass, the mass difference ΔM, the assumed integrated luminosity $\mathcal{L}$, the chosen center-of-mass energy $\sqrt{s}$, the corresponding signal cross section σ, the signal efficiency of the selection ϵ, the measured stau mass uncertainty $\delta m_{\tilde{\tau}_1}$ and the resulting precision on DM density $\delta(\Omega_{\rm DM}h^2)$.*

The second method works at higher beam energies but still below the mass thresholds of other sparticles, the idea being at such large energies, the signal cross section is big enough to collect a large event sample. The analysis also benefits from using explicitly the polarized beams to enhance the signal over background ratio. The stau mass can then be determined by analyzing the high energy spectrum. Indeed for the same benchmark point D', if $\sqrt{s}$ could be chosen to be at 600 GeV, sufficiently higher than the stau mass, a more precise stau mass and therefore DM density could be achieved even with a moderately small integrated luminosity of 300 pb^{-1}. The same method has also been applied to a SPS 1a inspired model for three different ΔM values. Again the precision on the stau mass and DM density improves as ΔM increases.

To summarize, our studies have shown that the detection and the mass measurement of the tau slepton, potentially important in view of the cosmological implications, is challenging in the so-called "co-annihilation" scenario. A forward veto to remove the $\gamma\gamma$ background down to very small angles is essential to reach an almost background free result, adequate to achieve the accuracy implied by the post-WMAP results in a model independent analysis.

In our analysis with method one, we have assumed an ideal detector for particle detection but with realistic detector acceptance as expected from a fast simulation program SGV [6], developed and tested at LEP. Some of the detector capabilities are not yet fully explored, e.g., the dE/dx information of the tracking device and possible different decay lengths (secondary vertex distributions) between the signal and the background events. The analysis in terms of the signal and background separation may still be improved using more sophisticated likelihood methods instead of simple cuts.

Nevertheless, the stau analysis in collisions with a crossing angle is likely to be more difficult (thought still feasible) than in head-on collision, only possible in the TESLA scheme. In a warm machine like NLC, the same conclusion could be reached provided that there is no degradation due to pile-up of several bunches in the forward veto (this may require some R&D for a very fast calorimeter).

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